"On the Movements of the Flame in the Explosion of Gases." By HAROLD B. DIXON, M.A., F.R.S. Received and Read June 5, 1902.

(Abstract.)

PART I.—*Historical Introduction.*

Bunsen, in 1867, made the first careful measurement of the rate at which an explosion is propagated in gases, and he also made the first systematic researches on the pressure and temperature produced by the explosion of gases in closed vessels. His results led him to the remarkable conclusion that there was a discontinuous combustion in explosions. When electrolytic gas, or when carbonic oxide with half its volume of oxygen is fired, only one-third of the mixture is burnt, according to Bunsen, raising the temperature of the whole to about 3000° C. No further chemical action then occurs until the gaseous mixture falls by cooling below 2500°. Then a further combustion begins, and so on, *per saltum*. These deductions were criticised by Berthelot, who pointed out that they assumed the constancy of the specific heats of steam and of carbonic acid at high temperatures.

Bunsen also stated that the rapidity with which the flame of the explosion spreads is synchronous with the attainment of complete combustion and of the maximum temperature.

In 1881 Berthelot and Le Chatelier independently discovered the great velocity with which the flame travels in gaseous explosions. Berthelot showed that this velocity was a constant for each gaseous mixture, and compared the rate of the "detonation-wave" (*l'onde explosive*) with the mean velocity of the molecules produced by the combustion before they had lost any heat. In the Bakerian Lecture for 1893, the author showed that Berthelot's theory did not account for many observed rates of explosion, and put forward the view that the explosion-wave travelled with the velocity of sound in the burning gases. Using the rates determined by the author, D. L. Chapman has argued that, if the explosion-wave is of a permanent type, an equation can be deduced from Riemann's formula by which the rates of explosion can be calculated if the specific heats are known, and *vice versâ*. The rate of the detonation-wave may therefore be utilised, according to Chapman, to determine the specific heats of gases at very high temperatures.

In 1883 Mallard and Le Chatelier published their researches on the combustion of gaseous mixtures. Using a delicate indicator, they found that rapidly exploding gases gave very high pressures for very small periods of time; these high but fugitive pressures they attribute

to the compression-wave which is propagated as the inflammation spreads from layer to layer. To obtain the mean pressure of the ignited mass of gas they had recourse to a less sensitive Bourdon gauge, and from the pressure-curves so registered they calculated the maximum pressures and temperatures of the explosion. Their results may be summarised in the statement that the maximum temperature of the explosion of moist electrolytic gas is 3350° C., and the mean specific heat of steam between that temperature and 0° is 16·6 (at constant volume), dissociation being very slight, if any, between these temperatures; on the other hand, the mean specific heat of CO_2 rises to 13·6 at 2000°, and above this dissociation begins. The simple diatomic gases (O_2, N_2, CO, &c.) show a rise of specific heat, though far less marked.

Berthelot and Vieille (1885) also determined the maximum pressures produced in the explosion of gases, and calculated the maximum temperatures. Their results were similar to those obtained by Bunsen, but they attribute the defect of pressure observed not to the inability of the gases to combine at the temperature reached, but to the great increase of the specific heats of the products of combustion.

On the other hand, Dugald Clerk contended (1886) that in an explosion the combustion is never completed instantaneously, and since the burnt gases are cooling while the unburnt are still combining, the observed pressures and temperatures fall short of those calculated for instantaneous combustion.

Mallard and Le Chatelier were the first to record the movements of the flame in explosions by photography on a moving film (1883). Failing to obtain images of the flame with mixtures such as $2CO + O_2$, they employed CS_2 with oxygen and with nitric oxide.

When the gases were ignited by a flame at the open end of a long tube, the flame was propagated along the tube for some distance with a uniform slow velocity. In the case of mixtures of carbon disulphide with nitric oxide, this period of uniform movement is succeeded by oscillations of the flame, which sometimes become of larger and larger amplitude and then die down, and sometimes give rise to the "detonation-wave." When carbon disulphide is mixed with oxygen, the preliminary period of uniform movement is shorter, and is succeeded immediately by the detonation.

Mallard and Le Chatelier draw attention to the fact that in these explosions—starting at the open end of a tube—the *development of the detonation-wave is not progressive, but always instantaneous.* When the mixture was fired near the closed end of a tube, the movement of the flame was uniformly accelerated until the detonation is set up. Their apparatus did not move fast enough to analyse the more rapid movement of the flame.

In 1888 von Oettingen and von Gernet analysed the flame by

means of a rotating mirror. Their photographs reveal, they state, the phenomena immediately succeeding the chemical combustion.

For although the flame of electrolytic gas appeared intensely bright, its spectrum only gave the sodium and calcium lines, and the most sensitive photographic plates showed "hardly a trace of the process." Failing to photograph the flame itself, the authors added finely divided salts to the tube, and found that the most brilliant pictures were given by cuprous chloride.

Their pictures show the passage of waves sharply reflected backwards and forwards from the ends of the tube, and gradually diminishing in intensity and velocity. These visible waves, according to von Oettingen and von Gernet, are not a picture of the process of combustion itself, but are compression-waves moving through the products of combustion after the explosion is completed. *The explosion itself*, they say, *is quite invisible.* Their photographs also show waves running nearly parallel with the primary waves. These secondary waves are particularly referred to as supplying conclusive evidence that *successive partial explosions* have taken place (starting from the electrodes) exactly as Bunsen imagined.

In 1884 Liveing and Dewar showed that the flame of an explosion in a glass tube exhibited the spectral lines of sodium and of calcium, and of iron when fired in an iron tube and examined end-on. When metallic salts were introduced in the form of powder, the corresponding lines were visible in the spectroscope. They made the interesting observation that the red lithium line was *reversed* when the explosion was made to travel towards the spectroscope, and they interpreted this to mean that the front of the advancing wave is cooler than the following part.

I have examined the spectra of many explosion-flames. The light produced by the explosions of electrolytic gas is mainly due to particles knocked from the glass. In the faint continuous spectrum shown by the flame the calcium lines stand out prominently. When the explosion travels first through a metal tube joined to a glass one in which the flame is photographed, the light is more intense near the junction. One can see the stream of luminous matter carried out of the metal tube.

The cyanogen explosions, however, give a continuous spectrum crossed by metallic lines and by the characteristic "cyanogen lines."

The luminous particles, whatever their nature, follow very closely the movements of the gas in which they float. When the spectra of the explosion-flames were photographed "end-on," I have never observed any reversal of a line in the advancing flame.

PART II.—*Photographic Analysis of Detonation-waves and their Reflections.*

[*In conjunction with* E. H. STRANGE, B.Sc., *and* E. GRAHAM, B.Sc.]

By throwing the image of the explosion tube on to a photographic film (Eastman's) fixed to a rapidly revolving wheel, we found that the flame could be sharply photographed, and its movements analysed, without the addition of any metallic salts to the tube.

The first point noticed in the photographs were (1) the sharpness with which the luminosity is set up; and (2) the uniformity of the detonation-wave. There is no evidence of any gradual heating up of the gases, but, on the contrary, the temperature appears to spring to its maximum with abrupt suddenness. The gas ignited by the detonation (including particles knocked off the tubes) remains luminous for some time after the wave has passed.

Many of the photographs show very distinctly the movements of the gas *en masse*, as it follows up the detonation-wave, comes to rest, and swings back again.

When the detonation-wave hits the closed end of the tube it is reflected back in a distinctly marked luminous wave, remarkable for its great luminosity. As this reflected wave starts back from the closed end it has at first to meet the gas moving bodily forward in the wake of the detonation-wave. As it continues backwards the gas it meets has less forward motion, then becomes stationary, and finally travels back in the same direction as the reflected wave. It follows, therefore, that the velocity of the reflected wave is at first retarded and afterwards increased by the motion of the medium.

The reflected wave produced by the collision of a detonation-wave with the closed end of the tube is mainly an intense compression-wave. The velocity of the reflection-wave may be readily compared with that of the detonation-wave. In the following table the average velocities observed in several gaseous mixtures are given, the velocity of the reflected wave being taken as nearly as possible at the point where the movement of the gas itself was nil.

Although the formula for the velocity of sound in gases is strictly valid for small displacements only, nevertheless it appeared of interest to calculate from the observed velocities of these reflection-waves what temperature they indicated in the gas, on the assumption that they were propagated as sound-waves. Of course to calculate the temperature from the velocity of sound it is necessary to know the ratio of the specific heats γ, and since in the case of carbonic acid and steam this ratio is very doubtful, a corresponding uncertainty must exist in the temperature calculated. But in the case of cyanogen burning to carbonic oxide, the products of combustion, carbonic oxide, and nitrogen are similar to air, and their specific heats either do not alter, or do not alter greatly, with rise of temperature. The velocity

Table I.—Velocity of Reflection-waves in Gaseous Explosions.

Mixture of gases.	Velocity of explosion-wave in metres per second.	Velocity of reflection-wave in metres per second.	Ratio of velocities.
$2H_2 + O_2$	2820	1538	1·83
$H_2 + N_2O$	2305	1383	1·67
$2CO + O_2$	1676	1078	1·56
$C_2N_2 + O_2$	2728	1230	2·22
$C_2N_2 + 2O_2$	2321	1129	2·06
$2C_2H_2 + 5O_2$	2391	1133	2·11

of sound in such a gas would therefore give an approximation to the temperature.

Now the velocity of the reflection-wave in cyanogen exploded with its own volume of oxygen is 1230 metres per second. Assuming γ to be unaltered by rise of temperature, and the velocity of sound in air at 0° C. to be 333 metres per second, the temperature of the gas where the reflection-wave was measured is given by the formula—

$$T = \left\{\left(\frac{V\sqrt{\frac{d_1}{d}}}{333}\right)^2 - 1\right\}273 = 3330^\circ \text{ C.},$$

where V is the velocity of sound, and d_1 and d the densities of the gas and air respectively under the same conditions. If, on the other hand, we assume (with Le Chatelier) that the specific heat at constant volume of diatomic gases rises with the temperature and becomes 7 at the temperature of this experiment, then the ratio γ_1 falls to 1·29, and the formula becomes:—

$$T = \left\{\left(\frac{V\sqrt{\frac{d_1}{d}\cdot\frac{\gamma}{\gamma_1}}}{333}\right)^2 - 1\right\}273 = 3672^\circ \text{ C.}$$

In the case of cyanogen exploded with twice its volume of oxygen, the first reaction probably consists in the burning of the cyanogen to carbonic oxide, which combines more slowly to form carbonic acid. How far this second reaction is completed when the reflection-wave is measured, it is impossible to decide. On the assumption that the specific heat of nitrogen is constant, and that CO_2 is 7·2, the velocity of the wave in the completely burnt mixture indicates a temperature of 4200° C.; on the assumption that the specific heats of CO_2 and N_2 are 20 and 7, the temperature indicated is 4780° C. On the other hand, if no carbonic acid had yet been formed, the temperature indicated for the mixture of diatomic gases ($2CO$, O_2, N_2) is 2880° C. ($C_V = 4{\cdot}8$).

In a similar manner the temperatures corresponding to the velocity of the reflection-waves have been calculated for the other mixtures, (1) assuming the ratio of the specific heats for a diatomic gas to be 1·41, and for a triatomic gas 1·28, and (2) assuming the ratio of the specific heats for a diatomic gas to be 1·29, and for a triatomic gas 1·11:—

Table II.—Temperatures of Exploded Gases calculated from the Velocities of the Reflection-waves.

Mixture.	I. γ for diatomic gas = 1·41. γ for triatomic gas = 1·28.	II. γ for diatomic gas = 1·29. γ for triatomic gas = 1·11.
$2H_2 + O_2$	3720° C.	4830° C.
$H_2 + N_2O$	3660	4130
$2CO + O_2$	4530	5250
$C_2N_2 + O_2$	3330	3670
$C_2N_2 + 2O_2$	4200	4780
$2C_2H_2 + 5O_2$	3980	4630

A glance at this table reveals the fact that, whether the specific heats vary or not, but on the assumption that combustion is complete in each case, the explosion of cyanogen to carbonic oxide, which, according to all observers, gives the brightest flash, and the highest pressure, also gives (apparently) the coolest combustion products a short time after the explosion-wave has gone by. The natural inference to be drawn from these figures is that in those mixtures where steam or carbonic acid, or both, are produced, the combustion is not complete at the moment the reflection-wave is measured.

PART III.—*On the Velocity of a Sound-wave in the Flame of Exploded Gases.*

[*In conjunction with* R. H. JONES, B.Sc., *and* J. BOWER, B.Sc.]

The interest attaching to the determination (even approximately) of the temperatures produced in the explosion of gases led us to attempt the measurement of the rate of a true sound-wave (of small displacement) in the gases produced by the detonation-wave.

In our first experiments the glass explosion-tube was fitted to a steel piece containing a tap of large bore, and a small bye-tap, and connected by a pipe to a steel bomb, in which a small charge of fulminate could be fired. The bomb and connecting pipe were filled with air, while the tube was filled with a mixture of cyanogen with two volumes of oxygen.

The lengths of the tubes were so adjusted that the sound-wave, started in the bomb by the detonation of the fulminate, should be

propagated through the air and cyanogen mixture, so as to meet the detonation-wave coming in the contrary direction before the latter reached the end of the tube. The detonation-wave was then photographed as it met the sound-wave. The photographs clearly show several sound-waves passing through the incandescent gases.

The rates of these sound-waves have been measured and the corresponding temperatures calculated. These values are given in Table III on the assumption that the combustion was complete.

Table III.

Number.	Velocity of sound-waves in explosion of $C_2N_2 + 2O_2$.	Calculated temperature. γ for diatomic gas, 1·41. γ for triatomic gas, 1·28.
1st	1116 metres per sec.	4100°
2nd	1014 ,,	3330
3rd	893 ,,	2530

It will be seen that the temperature calculated for the first sound-wave (4100°) is in close accordance with that calculated from the reflection-wave in the same mixture (4200°) given in Table II.

The experiment was next varied by the introduction of a thin iron membrane between the air and the explosive mixture. The shock transmitted through the air from the fulminate struck the flexible plate, and so propagated a wave of small displacement through the explosive mixture. This wave had very little effect on the movements of the gas in the wake of the detonation-wave, but its passage through the luminous gas was plainly marked. The gases were ignited as before, the lengths of the tubes being so adjusted that the first sound-wave met the detonation-wave about 1 metre from the membrane.

With the mixture $C_2N_2 + O_2$ three photographs were obtained in which the course of the sound-waves were fairly marked. The mean of several independent measurements made on each photograph gave as the velocity of the sound-wave *in the stationary gas* as 1250 metres per second. This velocity corresponds to a temperature of 3460° ($\gamma = 1{\cdot}41$), a number in very fair agreement with that calculated from the reflection-waves, viz., 3330° (Table II). This agreement indicates that the reflection-waves really travel with a velocity approximately equal to that of sound.

PART IV.—*On the Collision of Two Detonation-waves, and the Effect of Junctions in the Tubes.*

[*In conjunction with* R. H. JONES *and* J. BOWER.]

To study the effect produced in the collision of two waves of detonation, the explosion tube (of lead pipe) was bifurcated into two arms of equal length which were bent round and held the two ends of a strong glass tube, in the centre of which the two waves met. The joint between the lead and glass was made tight with india-rubber.

The photographs obtained with this apparatus were puzzling. Some of the "rebound waves" after the collision were much brighter and travelled (backwards) much faster than the detonation-waves themselves. Moreover, many photographs showed that the flame of the explosion had been affected by some impulses causing a sudden increase in its brightness and velocity, and producing a backward wave (analogous to a reflected wave).

The explanation of these appearances that first occurred to us was that the flame was preceded by invisible sound-waves, travelling more quickly than the flame in its initial phases; that these sound-waves became visible as soon as they met the flame moving towards them in the opposite direction (as in our previous experiments on sound-waves), and that, on the other hand, the visible flame meeting the sound-wave was affected by the sudden increase of pressure, and continued its journey with greater speed and luminosity. This explanation was at once destroyed when we found similar impulses in a flame which was sent through the apparatus in one direction only.

It next occurred to us that these impulses might be due to the explosion *catching up its own sound-waves*. If sound-waves are propagated through the gas from the point of ignition, the flame might lag behind the sound-waves at first and catch them after a run more or less prolonged. The sound-waves when overtaken might cause reflected sound-waves (made visible in the luminous gases), and the explosion itself might become more intense owing to the collision. Many experiments were undertaken to verify or disprove this hypothesis; but finally it was found that the explosion was affected as it passed through the junctions between the lead and the glass, and the "impulses" recorded in our photographs were due to the detonation-wave, damped down at the junction, being regenerated by fits and starts.

The flame is not retarded by turning round a corner, even when that is a sharp angle, nor is it damped down when the connecting junction is made of stout flexible rubber. After many trials we found that the only thing which mattered was the rigidity with which the glass and metal were connected together. Any packing (such as

rubber) which gave to a shock caused a retardation; when the glass was firmly cemented to the metal no retardation occurred. The anomalies met with in our collision experiments were thus accounted for, and the examination of collisions between true detonation-waves was proceeded with.

When two detonation-waves come into collision the tube remains brightly luminous at the point of contact for some time, and two reflected waves are sent backwards with velocities which increase at first, owing to the movement of the gas through which they are propagated.

A comparison of all the photographs shows that the gases are more luminous after a collision than when the explosion-wave strikes a flat surface of metal fastened at the end of the tube. The reflected waves in the two cases are similar in character, but the reflection generated by collision with another detonation-wave seems always to travel slightly faster. If we were dealing only with waves produced mechanically, the reflected waves would be exact copies of the incident waves with velocities reversed—in both cases. But in the detonation-wave we have chemical as well as mechanical action, while the reflected wave is mainly mechanical. We should expect therefore the reflected waves to travel more slowly than the incident waves, but we should also expect the reflected waves to travel with the same velocity whether they were produced by collision with a rigid diaphragm or with a similar and equal wave travelling in the opposite direction—*unless there was some chemical difference involved in the two kinds of collision.*

Our photographs have shown that the wave of detonation has certain characteristics by which it may readily be recognised:—

(1.) It starts suddenly, throwing back a strongly luminous wave through the burning gases, and leaving a dark space where it started.

(2.) It travels with constant velocity unless it traverses a junction not rigidly attached; after being damped down by such an obstacle it recoups itself and again starts with abruptness.

(3.) On collision with a similar detonation-wave moving in the opposite direction, or with a rigid diaphragm, it sends back a reflected wave not so rapid as itself, and as a rule not so luminous.

In the case of the more luminous explosions, *e.g.*, those of cyanogen, acetylene, and carbon disulphide mixtures, the reflected waves were less luminous than the detonation-wave; but in the case of the less luminous explosions, *e.g.*, those of hydrogen and carbonic oxide, which depend largely for their light on the particles detached from the tubes, the waves reflected from a collision were sometimes more luminous than the detonation-waves themselves.

PART V.—*On the Initiation of the Detonation-wave and on the Wave of Retonation.*

[*In conjunction with* R. H. JONES *and* J. BOWER.]

Our photographs show abrupt changes in the acceleration of the explosion before the final spring which marks the detonation-wave. These sudden changes are accompanied by a luminous wave thrown back through the ignited gases.

The strongly luminous wave thrown back from the point where the detonation is started we call the "Retonation-wave." A study of a number of photographs leads to the conclusion that the retonation is faster and more luminous when no other bright waves have been thrown back by the advancing flame before the point of detonation is reached.

The collision of two flames, in which detonation had not yet been determined, gave rise to reflected waves more rapid and more luminous than the incident waves. Now these reflected waves could not owe their increased velocity to the mechanical impact, which could only result in the reflected waves being copies of the incident waves. It is evident then that chemical action must occur to assist these reflected waves, and, therefore, the combustion is obviously not complete when these waves return. From this it would appear probable that the period before the detonation is distinguished not only by a slower propagation of the flame, *i.e.*, of ignition, but also by a slower process of combustion.

At the point of detonation the rapid rise of pressure produces not only the forward wave—that of detonation—but also a backward wave of compression into the gases still slowly burning behind it. This compression-wave must raise the temperature of the ignited gases and quicken the residual burning; its propagation would thus be analogous to that of the detonation-wave, but modified by the extent to which the slow combustion had proceeded.

The retonation-wave attains its greatest rapidity and brightness when it is developed at the closed end of a tube, *i.e.*, when the gas is fired at such a distance from the closed end that the explosion, gradually increasing in intensity, just reaches the detonation point as it arrives at the stopper. Under such conditions the reflected wave is superposed on the wave of retonation, and the result is a wave which cannot be distinguished from a detonation-wave.

As regards the dark space formed at the point where the detonation- and retonation-waves originate, it is no doubt a space of cooler gas. It persists for some time, and its damping effect on the passage of collision-waves can be observed in several of the photographs.

PART VI.—*On the Initial Phases of the Explosion.*

[*In conjunction with* R. H. JONES *and* J. BOWER.]

As several of our photographs had shown that the flame in the period of acceleration was overtaken by a more rapidly moving wave, we photographed the *beginning* of an explosion of cyanogen with oxygen, and found that the bright flame which overtook the primary flame came *from the end of the tube near the firing wires.* The "kick-off" which the explosion gets from the closed end, apparently enables the reflected wave to overtake the original wave of combustion. When the gases are fired by means of wires *just* penetrating the stopper closing the end of the tube, the explosion proceeds more slowly, and without disturbance by any sudden changes of acceleration until at last the point of detonation is reached. The photographs of these explosions are in marked contrast to those taken when the firing wires were 3 inches from the end of the tube. In the less rapid explosions it is seen that the flame does not travel direct to the near end of the tube, but while still a short distance from it recedes and again approaches with an oscillatory motion, which is repeated before the flame finally reaches the end of the tube. From the point where the flame is first checked a luminous wave is seen running back and overtaking the main flame, which at this point acquires greater brightness and velocity. From the point of collision where the faster overtakes the slower flame, a reflection is thrown back to the near end of the tube where it is again reflected.

Now when an explosive mixture is fired by a spark, the suddenly ignited gases must expand and transmit a compression-wave in both directions. This travels with the velocity of sound in the unburnt gas, and will be reflected from the end of the tube. The propagation of the flame from the firing point is, in most gaseous mixtures, less rapid than the velocity of sound in the unburnt gas, but the rate of propagation of the flame augments much more rapidly in some mixtures than in others. If the tube is a long one the flame will overtake the sound-wave after a more or less prolonged chase, according to the nature of the mixture. But if the tube is short the sound-wave may reach the end of the tube and return as a reflected wave to *meet* the flame, which is still advancing. Our measurements show this to be the origin of the "return-wave" from the end of the tube.

When gases are fired in the centre of a long tube the phenomena of explosion are simple; when they are fired in the centre of a short tube, the sound-waves generated reach the end of the tube before the flames, and the impact of their reflections with the flames produces cross-waves of great intricacy and beauty.

Part VII.—*Further Experiments on the Initial Phases.*

[*In conjunction with* B. Dawson, B.Sc., *and* L. Bradshaw, B.Sc.]

1. *Le Chatelier's Hypothesis of Discontinuity in the Explosion.*

Many photographs show a peculiarity at the point where a less luminous line is succeeded abruptly by a more luminous one. The lines photographed do not appear *continuous*, but the more luminous line appears to start from a point not yet reached by the less luminous one. The point of collision also of two waves appears to project in front of the waves which are meeting. It appeared to me at first as if these appearances might be due to invisible waves advancing in front of the visible ones, but as I found that they only showed where the luminosity of the lines was in marked contrast, and disappeared entirely when the films were not sensitive, or the contrast of luminosity was diminished, I came to the conclusion that the effect was due to halation on the photograph, the brighter lines being enlarged.

But in 1890 Le Chatelier, relying on the same kind of evidence, put forward the view that the wave of detonation starts *in front* of the variable wave (which is increasing in velocity), and originates in an invisible wave which is proceeding in front of the visible wave, and with a velocity equal to it.

This definite judgment of the French experimenter compelled us to re-examine the question. We attempted at first to decide the matter by photographing an explosion as it passed from a less luminous mixture into a more luminous one; but we could not succeed in making the transition sufficiently sudden.

We did, however, succeed in obtaining sudden changes of brightness by introducing a layer of "Welsbach" salts (a mixture of thoria and ceria), and having the rest of the tube quite clean. Although to raise the salt from the glass and to render it incandescent must take some time, nevertheless the photograph shows a small but distinct break in the line of detonation similar to that in question.

It is, of course, easy to show the enlargement due to brightness. If a tube is filled with a mixture giving a luminous explosion, and the explosion is photographed while half the tube is covered over; and if the tube is then filled with a mixture giving a less luminous explosion, which is photographed on the same film while the first half of the tube is covered, a photograph is obtained which shows a greater discontinuity than any of those in question.

Another way of showing the same thing is to photograph a thin platinum wire stretched by weights, and rendered luminous by an electric current. If a second wire is brought to touch the first so as to divide the current, the portion of the wire which carries the whole current is more luminous than the other portion, and the photographs make it appear of far greater diameter.

The evidence against Le Chatelier's view may thus be summarised:—

1. Its supposed effect is only seen when the contrasts are strong, and not on photographs of the same phenomena in which the contrasts are not brought out.

2. It can be initiated in various ways by means of contrasts.

3. The same effect is seen in the collision of two detonation-waves, but Le Chatelier does not suppose that the "invisible wave" can precede the detonation.

2. *Repetition of v. Oettingen and v. Gernet's Experiments.*

The very short time required for the explosion in electrolytic gas to raise the Welsbach oxides to incandescence was strong evidence against the view held by v. Oettingen and v. Gernet, viz., that the detonation of electrolytic gas is invisible, and that the salts present in their experiments only became luminous after the combustion had been for some time complete. Our previous experiments had also shown conclusively that the detonation is not set up *at once*, but only after the flame has run some distance which varies with the nature of the mixture and the position of the spark. But to place the matter beyond all doubt we have repeated their experiments, using a tube of the same size and construction as theirs filled with electrolytic gas, but without the addition of any salts. By careful development the course of the flame can be seen on the negatives from the firing wire. In all cases the explosion begins slowly and has slight luminosity until the retonation-waves are started by reflection from the ends of the tube. Some of our photographs closely resemble in detail those published by Oettingen and Gernet, but they show the initial movements of the flame which are lacking in their photographs. The reflections of the two waves often run nearly parallel, but the stronger wave usually catches the weaker and coalesces with it. The photographs thus make clear how "secondary" waves running parallel with "primary" waves may be produced from a *single* explosion in a short tube.